A 30 kW, 3 kHZ, SINGLE GAP, LINEAR THYRATRON†

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Abstract

This paper presents the results of the third Phase of the Linear Thyratron program at Spectra Technology, Inc. The design goals of >2 kHz rep rate with switching rates of $>10^{11}$ A/s and $>10^{12}$ V/s were achieved. The maximum holdoff voltage, however, was 60 kV rather than the desired 100 kV. This is partially due to damage caused by modulator failure in early testing. The maximum demonstrated average switching power was limited to 30 kW (5.4 nF at 60 kV and 3 kHz rep rate) for a burst of 5 pulses instead of the desired 50 kW. Instantaneous switching powers of >130 MW were demonstrated. All experiments used a cold dispenser cathode of 10 cm linear length and the gases were usually pure H_2 or He, although mixtures were briefly investigated. Due to time and funding constraints further modifications were not possible.

Linear Thyratron Modifications

Figure 1 shows the Phase 2 and Phase 3 Linear Thyratrons (LT's). The results of both the first and second Phases have been previously reported[1],[2] and will only be used for comparison in this paper. Contractual and budget constraints limited Phase 3 to modifications of the Phase 2 LT. A complete redesign was not possible.

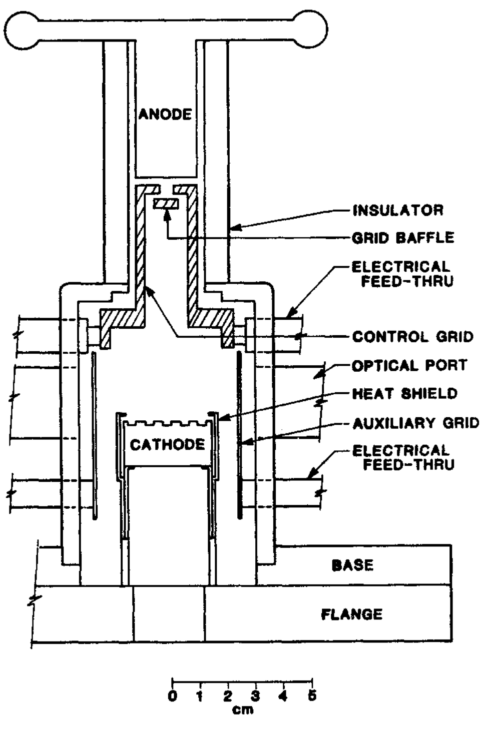

Figure 1a. Schematic of the Phase 2 Linear Thyratron.

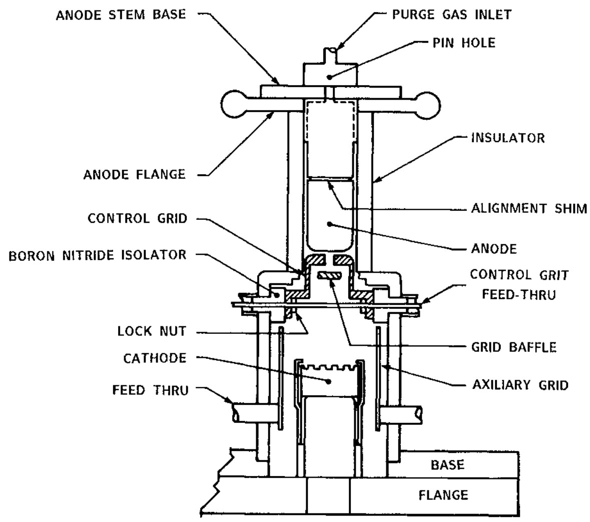

Figure 1b. Schematic of the Phase 3 Linear Thyratron.

The most obvious modification in Phase 3 is the lower location of the anode-control grid gap in the insulator. The intention is to decrease the length of the low field drift region in the control grid and improve the switching time. Lowering the gap has the disadvantage of raising electric field stresses across the dielectric surface and at the triple point where the insulator rests on the LT body. These regions were carefully modeled with the PANDIRA electro-magnetostatic codes to limit the field stresses across dielectric surfaces to <100 kV/cm and on conductor surfaces to <1 MV/cm.

Further modifications increased the slot width, radiused the slot corners and increased the baffle-slot gap. These modifications are intended to improve switching time, while maintaining voltage holdoff. The anode stem is split to allow shimming and enable the anode and control grid faces to be aligned to better than 0.002", or 2% of the gap. The anode flange has been stiffened and the top portion of the anode stem is hand finished to give a slip fit into the insulator. This ensures a uniform anode-dielectric gap around the anode stem. The final modification added a 0.025" radius diamond pinhole to the anode to allow purging of the anode-control grid-slot-insulator regions at a few sccm. Gas is fed to the pinhole through a coiled glass tube for high voltage holdoff.

Assembly begins with accurately locating the control grid and baffle within the LT body and then placing the insulator around the control grid. When the control grid-insulator spacing is set, the anode

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flange is attached to hold the insulator in place, and the anode stem is attached through the flange. The whole assembly is then attached to the cathode flange. This procedure allows tight tolerances to be held for all critical dimensions, with emphasis on parallelism rather than absolute dimensions.

All the internal metal pieces are stainless steel. While this is adequate for most purposes, a molybdenum plated anode tip and, perhaps, control grid would be preferable, as damage to both these surfaces was observed on the Phase 2 LT.

Modulator Modifications

In order to meet the goals of this Phase it was necessary to rebuild the modulator circuit. The Phase 2 modulator was designed for ≤200 Hz operation at <100 kV compared with >2 kHz at ≥100 kV in this Phase. Figure 2 shows the modified modulator circuit in its high rep rate and high voltage configurations. The pulse transformer from Phase 2 was designed for 200 Hz and could not be replaced.

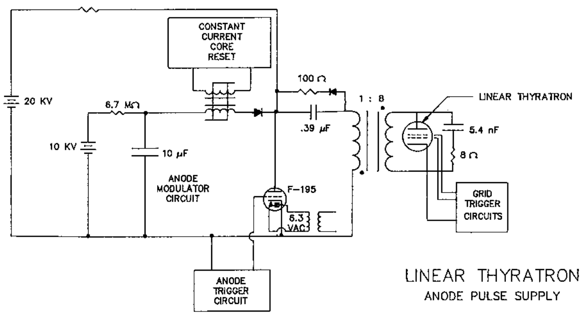

Figure 2a. Modulator Circuit for 0-120 kV Testing.

It was necessary to add the saturable inductor to enable the modulator thyratron to recover and yet operate at high rep rate. Even with the saturable inductor, the modulator is limited to 1 kHz in its standard configuration (Fig. 2a). For higher rep rates the modulator switch hangs up and dumps the storage capacitor. This configuration is capable of delivering up to 120 kV to the LT circuit, however.

In order to improve the rep rate the circuit was modified to that shown in Figure 2b. This configuration uses the transformer to help the modulator switch recover and enables operation to slightly greater than 3 kHz. Unfortunately this configuration floats the primary of the pulse transformer at high voltage and requires reversal of either the primary or secondary leads to maintain the correct output polarity to the LT circuit. This places high and low voltage windings in close proximity to each other and to the core and breakdown occurs at any output greater than 60 kV. This breakdown hangs up the switch and dumps the storage capacitor through the shorted transformer. Large negative voltage transients are observed in the secondary.

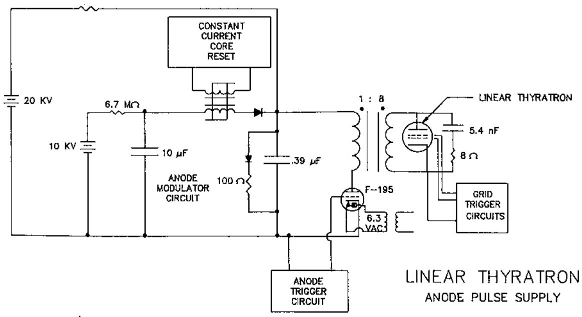

Figure 2b. Modulator Circuit for 0-3 kHz Testing.

It was while inadvertently discovering this failure mode that the LT may have been damaged, as discussed later. The LT circuit is a RLC circuit with the inductor winding removed from the Phase 2 circuit to reduce circuit limitations on both current switching times and peak currents. The stray inductance is still significant and the circuit is slightly underdamped.

Experimental Results

Voltage Holdoff

60 kV Limit: The modified LT was first tested up to 50 kV in air to ensure that the system was completely vacuum tight and operational. This was when the rep rate limit of the circuit of Figure 2a was discovered and modified to that of Figure 2b. The LT was then immersed in oil and tested at higher voltage. At 60 kV the LT appeared to be prefiring, independent of gas type or pressure. Every time this apparent prefire occurred, however, the modulator switch would hang up, as previously mentioned. A prefiring LT would not cause this to happen and it was discovered that the pulse transformer was breaking down internally. The LT is not designed for the large negative voltage and current transients which occurred and may have been damaged. Even when the modulator was reconfigured for high voltage operation the LT would not hold off more than 60 kV.

There is another possible explanation for the lower than expected voltage capability of the LT. Windows at the ends of the LT body allow observation and diagnosis of the cathode-control grid region. When LT prefire is due to Paschen breakdown in the anode-control grid gap, a discharge is observed in the cathode-control grid region. At the 60 kV breakdown limit this discharge is not seen. Light is observed from the side of the control grid, indicating that the breakdown path is down the control grid-insulator gap to the LT body. The breakdown occurs at the same location every time.

The hole in the major insulator is not completely symmetrical, and varies in width by as much as 0.01". This, coupled with the possibility that the insulator may not have been accurately placed around the control grid, may lead to regions of the control grid-insulator gap being significantly wider than the

0.030" design, which was also the value assumed in the modeling. A wider gap would allow the high field region to penetrate further down the gap than designed, decreasing the holdoff capability.

A combination of reverse current damage and field penetration into the control grid-insulator gap would explain a large part of the limited holdoff capability. The stainless steel anode and control grid are particularly prone to arc damage and sputtering under these conditions. If the anode-control grid gap were deeper into the insulator, this problem would be decreased, at the expense of switching rate.

Once the LT has been immersed in oil it is a delicate and time consuming procedure to dismantle it without risking serious poisoning of the dispenser cathode. The program expired before an "autospy" could be performed. Until this can be done the preceding observations must be considered conjecture, and the LT a 60 kV switch until proven otherwise.

Paschen Breakdown: Figure 3 shows the measured voltage holdoff limits as a function of gas pressure for H_2, He and a mixture of 60% H_2 and 40% He. The pure gas data was obtained with the purge flow on. This was not possible with the mixture and limited the number of shots which could be taken. These data are compared with the results from the previous Phase. For voltages below 60 kV the new LT performs better than the Phase 2 device. This is due to the care taken in holding critical dimensions as closely as possible, and to the rediusing of the control grid slot.

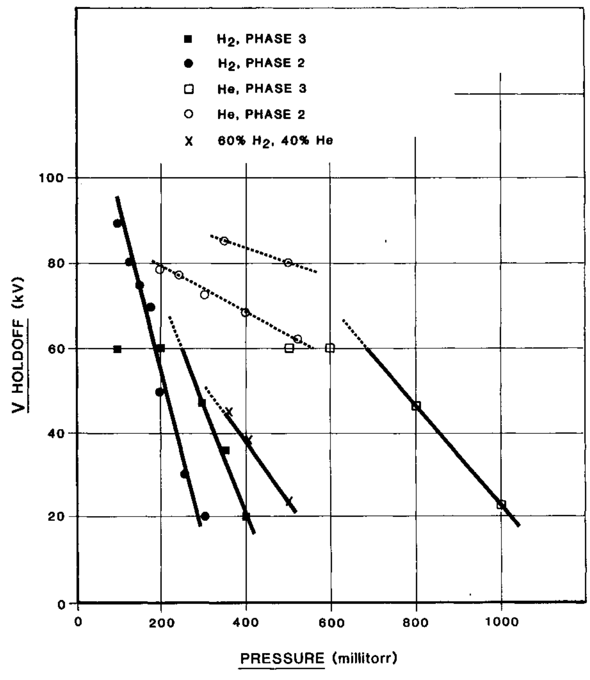

Figure 3. LT Holdoff Voltage as a Function of Gas Pressure for Phase 2 and Phase 3 Devices.

The addition of even small amounts of H_2 into He appears to degrade the holdoff capabilities of the LT below the He values. No "magic" mixture was observed to yield superior performance. This is not totally conclusive since mixtures were only investigated in a cursory manner and in non-optimum conditions.

The Phase 3 data shown in Figure 3 required a 300 V negative grid bias because of the wide slot and loose baffling.

Flow of a few sccm greatly improved shot to shot repeatability, and allowed the data to be acquired on a more or less continuous basis, rather than the frequent flush and fill required in the previous Phase.

Switching Rates

One of the major goals of this Phase was to demonstrate respectable current and voltage switching rates, even for this highly non-optimum geometry. Figure 4 shows current and voltage traces in 100 mTorr He with a negative 300 V grid bias and 50 kV charge voltage. The leading edges of the traces are difficult to analyze due to the writing speed of the oscilloscope, but showed more clearly on the Polaroid negative. The current trace rises to 1 KA in 10 ns for a dI/dt of 10^{11} A/s. The current monitor is a Pearson probe, model 110. The specifications for this probe give a rise time of 20 ns for a square wave pulse. Furthermore, the same minimum rise time is observed in both H_2 and He for a range of pressures. The value of 10^{11} A/s is therefore diagnostic limited and is a lower bound for the maximum dI/dt.

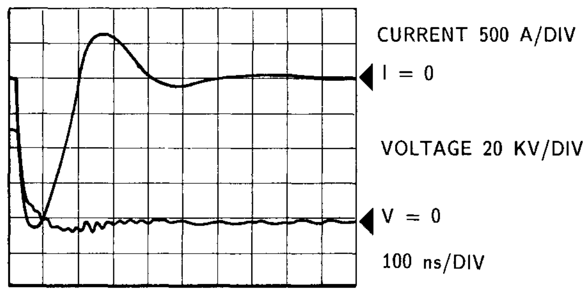

Figure 4. VI Switching Characteristics. Gas = He, Pressure = 100μ Voltage = 50 kV

The voltage trace drops to 7 kV in 40 ns for a dV/dt of 10^{12} V/s. As the voltage is decreased further below the holdoff limit the switching rates decrease.

The highest switching rates are only observed after the LT has been run a while. When the system is first turned on the switching rates are very low. Figure 5 shows an example when the device is first turned on with 100 mTorr H_2 and 44 kV. In this case dI/dt = $7X10^9$ A/s and dV/dt = $5X10^{11}$ V/s.

The dispenser cathode has been removed at least 10 times from the various versions of the LT and has

been run cold for many thousands of shots. The likelihood of poisoning and/or depletion of the cathode is high. If the LT is run at about 1 Hz for a few minutes with a gas purge flow and the voltage gradually increased then it operates repeatably and reliably.

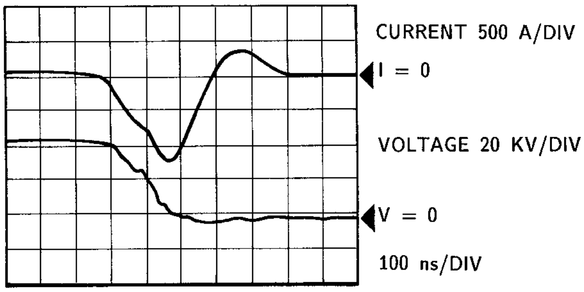

Figure 5. Startup Switching Characteristics. Gas = H_2, pressure = 100 μ, voltage = 44 kV.

Rep Rate and Switching Power

The LT was tested up to 60 kV to over 3 kHz. Figure 6 shows a burst of 5 shots at 3 kHz with a 34 kV charge. The variation in voltage is due to both droop in the storage capacitor and partial saturation of the pulse transformer core. At rep rates slightly greater than 3 kHz the modulator switch hangs up. The first shot is at higher voltage and its current trace does not appear. The current traces show ≈100 ns jitter between the second and last shots, with the middle two almost indistinguishable. The jitter is mostly due to the different voltages at which each pulse was switched.

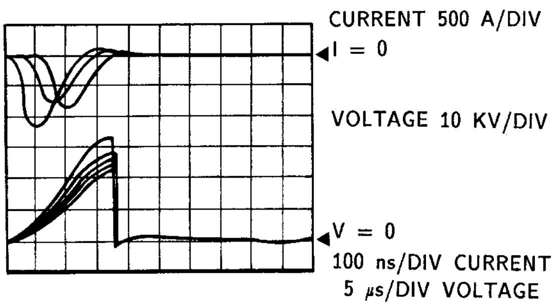

Figure 6. VI Traces for a Burst of 5 Pulses at 3 kHz in 800 μ He. Initial voltage = 34 kV.

The same rep rate limit was observed up to 60 kV, but the jitter becomes much worse and saturation of the transformer core leads to erratic traces making clean data difficult to obtain.

These limits are modulator governed, and the rep rate capability of the LT has not been fully tested or demonstrated.

With a 5.4 nF capacitance at 60 kV the switched energy is 9.7 J/pulse and at 3 kHz the mean switched power is 29 kW. These values could be raised by increasing the capacitance. The energy per pulse and pulse length limits of the LT are unknown.

The highest switched current was 2.25 KA at 60 kV in 100 mTorr He. This corresponds to a peak instantaneous switching power of 135 MW. There are no signs of saturation by either the cathode or the control grid slot in either He or H_2 and the ultimate current capability of the LT has not been reached.

Summary

This Phase of the LT program has demonstrated the value of electrode and grid profiling and field modeling in optimizing thyratron performance. The linear geometry has some intrinsic advantages which have been discussed previously[1],[2]. It also has the benefit of being truly two dimensional in geometry, lending itself to easy diagnosis. The knowledge learned over the three Phases of this program is equally applicable to conventional geometries.

Even though the desired holdoff of 100 kV was not reached, the goals of >2 kHz with dI/dt >10^{11} A/s and dV/dt >10^{12} V/s were achieved in a very non-optimum geometry with switching voltages up to 60 kV and a single gap. The low holdoff voltage is probably due to both damage caused by modulator failure in early testing and an uneven control grid-insulator gap.

An obvious extension of this program is to build a thyratron for optimum compactness and performance rather than ease of diagnosis, using the results of the LT program. The switch may or may not have a linear geometry, depending upon the desired characteristics.

[1] R.A. Petr et.al. "A Summary on Linear Thyratron Development," 5th IEEE Pulsed Power Conference, Arlington, VA., 1985.

[2] M.J. Kushner et.al. "Voltage Scaling of a Single Gap Linear Thyratron to >90 kV," 17th Power Modulator Symposium, Seattle, WA, 1986.

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